ORIGINAL

ORIGINAL FILE

BEFORE THE

Federal Communications Commission

RECEIVED

SEP 8 1992

MAIL BRANCH

In the matter of	)	
	)	
Establishment of an Advisory	)	
Committee to Negotiate Proposed	)	CC Docket No. 92-166
Regulations in the 1610-1626.5	)	
and 2483.5-2500 Frequency Bands	)	
	)	

RECEIVED

SEP - 9 1992

FEDERAL COMMUNICATIONS COMMISSION
OFFICE OF THE SECRETARY

COMMENTS AND APPLICATION
OF
CELSAT, INC.

Celsat, Inc. ("Celsat"), pursuant to Public Notice in the above-referenced docket released August 7, 1992 (DA 92-1085), hereby respectfully submits these comments in support of the proposed negotiated rulemaking process and, concurrently herewith, applies for full participant status in the negotiations to follow.

Support for the Negotiated Process

The Commission has under consideration the formation of an Advisory Committee to address the issues leading to a feasible solution and Notice of Proposed Rulemaking in ET Docket No. 92-28 which will thereafter govern the shared use of the L/S-Band RDSS spectrum for Mobile Satellite Service (MSS) purposes. Specifically, the Commission has identified the following two issues for consideration by the Advisory Committee:

1. What technical rules should be adopted for MSS service so as to maximize the sharing of the spectrum and the capacity for multiple entry; and

2. What technical rules should be adopted in order for this service to co-exist with other allocated services.

While addressed specifically to the "RDSS" bands, the procedures and proposals to be developed by this committee will undoubtedly be influential in the allocation processes not only for this band but also any alternative bands identified for allocation among MSS or similar shared services.

Celsat has not yet filed an application to offer MSS services in the RDSS band but intends to do so in due course.[1]

---

[1] CELSAT has faced a "chicken and egg" situation since its inception: On the one hand, neither the RDSS spectrum nor any other spectrum allocation in the Commission's rules provides for the concurrent use of the same spectrum band for both terrestrial and space-based hybrid cellular/PCS-like services. Without an "allocation" there was no legal basis for a CELSAT application. Thus, the logical first step required CELSAT to file a rulemaking proposal -- which it has done. (RM-7927) But on the other hand, not having filed an application, CELSAT's opponents argue that its hybrid CELSTAR system has no right to be considered concurrently with the "Big LEOs" as a candidate for the RDSS spectrum.

As to the opponents' contention it suffices to point out that CELSTAR is not a mutually exclusive system. As CELSAT has made clear (see, for example, CELSAT letter to Chairman Sikes, July 26, 1992), CELSTAR can share the RDSS spectrum in several ways, either with Motorola's IRIDIUM, with the Gang-of-Four, or any combination of them. Thus, irrespective of whether CELSAT failed to meet the June 3, 1991 cut-off for its hybrid application, because (a) the RDSS spectrum rules contemplate shared systems; (b) there is no absolute deadline under the rules precluding an additional cut-off date for still additional applications for systems capable of sharing with those systems considered in an earlier cut-off group; (c) as yet, there are no technical or legal limits on the number of systems which shall be permitted to share the RDSS spectrum; and (d) CELSTAR can share efficiently with any existing applicant for that spectrum, there is no legal basis for excluding CELSAT from either the contemplated negotiations or as a candidate for the RDSS spectrum on the procedural ground that CELSAT has not yet filed an actual application.

However, CELSAT has filed a petition for rulemaking (RM-7927) and an application for pioneer's preference (PP-28) through which it seeks rule changes and authority to use these or alternative bands for its very novel and extraordinarily spectrally efficient hybrid personal communications network (HPCN) concept. From its position more or less as an outsider CELSAT has observed with great concern the apparent inability of the most active parties (i.e., Motorola, the Gang-of-Four, and ASMC) to identify and agree on a sound technical means by which the Commission's twin objectives of maximum sharing and multiple entry might be attained in the RDSS band. To the extent that band sharing continues to be misunderstood or perhaps even deemed impossible, CELSAT risks being unnecessarily and unfairly excluded from the RDSS band.

CELSTAR is a CDMA spread spectrum system and, as such, CELSAT is convinced of the inherent ability of its technology to support services on a band sharing basis. Properly managed and with systems of near equal capacities, the total band capacity with band sharing can be greater than that realized by a single band occupier. But the opposite is more likely to be true. A given band has a real practical limit on the channel capacity which it can support through band sharing mechanisms. Attempts to approach or exceed this capacity through band sharing can result in a significant loss of total realized band capacity.

An original technical monograph by Dr. Jack Mallinckrodt of CELSAT on the issue of band sharing allocation limits and a methodology for attaining it was submitted as part of CELSAT's

Consolidated Reply filed on April 24, 1992. A revised version of this paper, entitled "BAND-SHARING COORDINATION OF WIDE-BAND MOBILE SATELLITE SERVICES" ("Mallinckrodt paper"), focuses on the issue of greatest interest to the proposed Advisory Committee. It is attached to these comments as a submission to and is hereby proposed by CELSAT for consideration during the negotiations.[2]

First, the Mallinckrodt paper primarily addresses only compatible CDMA signaling formats such as those proposed by CELSAT and the Gang-of-Four applicants.[3] Specifically, CELSAT's paper:

1. Develops a methodology for normalizing the design capacities of diverse systems so that they can be compared on a level playing field with respect to spectral occupancy and flux density;

2. Develops simplified expressions for the loss of such normalized capacity due to band sharing, and expressions for the resulting total US circuit capacity afforded by the totality of all such band sharers;

---

[2] CELSAT's Mallinckrodt paper does not address the second issue set forth in the Public Notice of ensuring co-existence in the RDSS band with other service providers, such as the radio astronomy operations and GLONASS. However, as a potential sharer in this band CELSAt can at least ensure that it will be able to limit its operations so as not to interfere with such other users in ways that the other applicants might not be able to duplicate.

[3] CELSAT has also proposed that it would be willing to and is technically capable of sharing the RDSS band with IRIDIUM in either of two ways -- (1) allowing IRIDIUM to have 10.5 MHz in the L-Band while CELSAT would use the S-band on a time duplex basis, or (2) by pairing the S-Band for CELSAT with a comparable amount of spectrum from another band. See, CELSAT Consolidated Reply; also, CELSAT letter of July 26, 1992 to Chairman Sikes. No other applicant has expressed a comparable ability or willingness to share spectrum with Motorola on either basis (although Motorola has picked up on CELSAT's proposal and has subsequently suggested that the latter approach above should be considered as a solution offered only to the Gang-of-Four).

3. Gives example calculations of individual and joint US circuit capacity of a band, under alternative flux density allocation strategies; and

4. Argues by example that in the CDMA band sharing environment, the allocation of flux density takes on a role of equal importance with the allocation of bandwidth in an FDMA environment.

Second, Mallinckrodt points out that to maximize spectrum sharing and multiple entry in the RDSS band the Commission must allocate on the basis of flux density. Moreover, notwithstanding the Commission's condition that any sharing proposal must conform to all relevant ITU standards, CELSAT urges the relaxation of the power flux density limits over the United States as has been proposed by CELSAT and several applicants.

Third, while Mallinckrodt suggests alternative criteria for allocating flux density in order to achieve different sharing policy objectives, if the objective is simply to maximize the number of participants then the paper suggests that each sharer receive a flux density allocation equal to exactly what it has previously requested.[4] The results of such a policy is illustrated in Case No. 3 of Table 2 of the Mallinckrodt paper.

[4] The practical PFD capacity of each proposed system is limited by each satellite's prime power and antenna design. Thus, for example, there is little benefit to be gained for some applicants by allocating an equal portion of the available PFD capacity available for sharing if, to do so, might result in one or other applicant receiving more access to PFD then what its system has a capacity to use. On the other hand, while an equal PFD allocation across the board might be wasteful from the standpoint of an applicant whose system cannot use the full amount of an equal allocation, equal allocations might penalize yet another system whose design is optimized at a greater level of PFD utilization.

Fourth, the Mallinckrodt paper shows how PFD limits can be shared to achieve different desired results. If, for example, the policy objective were to maximize use of the spectrum (as measured by the number of available equivalent voice grade channels) then the available PFD would be allocated in some proportion to the efficiency of the participating systems. (This is illustrated by Case No. 4.) In any event, whenever spectrum sharing is to be utilized, there must be some loss in U.S. MSS capacity.

Finally, CELSAT's suggested method of CDMA band sharing offers an inherent advantage in that, on the one hand, it is expandable (within reasonable limits) and thereby capable of accommodating a variable number of sharing participants (subject to their CDMA compatibility). Thus, for example, new MSS entrants can come and go over time without a need to hold spectrum in reserve for specific future licensees. On the other hand, no spectrum goes wasted (i.e., unused) and the quality of service in terms of reduced interference between and among operating applicants improves automatically whenever any participant either drops off or otherwise enters any mode in which it fails to utilize all of its allocated flux density. Other possible flux density allocations using Mallinckrodt's analytical tool make it theoretically possible for one or other especially efficient system to actually negotiate for the flux density allocation of lesser efficient participants thereby enhancing the performance potential of the more efficient system and possibly that of others as market forces dictate.

Understandably, CELSAT is vitally interested in the outcome of the proposed Advisory Committee proceedings. As CELSAT has shown, if the Mallinckrodt method of spectrum sharing is adopted, there will enough RDSS spectral capacity to not only accommodate all the economically viable CDMA-based LEO systems now under consideration, but to also accommodate CELSAT as a U.S. based GEO system -- and with a drastic net gain in terms of overall U.S. MSS capacity. On the other hand, if any lesser efficient sharing scheme is adopted, CELSAT stands to be foreclosed as a major contributor in the MSS field. Thus, CELSAT's interest is believed to be aligned with that of the FCC in insuring that the rulemaking and allocation process maximizes the US benefit in terms of spectral utilization efficiency. CELSAT therefore submits that the proposed negotiated rulemaking process very definitely should go forward and that CELSAT should be a part of it.

CELSAT Requests To Be Included As A Full Participant

CELSAT has placed before the Commission a novel geostationary satellite proposal for a mixed use, voice/data/fax/video/RDSS service using the RDSS spectrum. CELSAT's novelty lies, in part, on its proposed hybrid space/ground cellular concept and its very large geostationary satellite/antenna combination. No party, including the "Big LEO" applicants themselves, found any serious technical fault with CELSAT's proposal, and what few minor criticisms they made have been responded to fully by CELSAT.

Although the text of the Commission's Notice of Proposed Rulemaking adopted on August 5, 1992 in ET Docket No. 92-28 has not yet been released, the Commission's open meeting and news reports of the Notice indicate that the Commission has recognized the benefits of CELSAT's hybrid concept, but apparently is inclined to take it up in a different context and outside the RDSS L/S_Band spectrum. CELSAT believes that this could be unfortunate, but at the very least should not have to be necessary. To the extent any such Commission decision to consider CELSAT separately might have been prompted by an unawareness of CELSAT's total technical compatibility with either the IRIDIUM system or those of the Gang-of-Four, CELSAT hopes to dispel such notion -- it is compatible, and as discussed above, it can share the RDSS spectrum with either group of applicants. Moreover, CELSAT is proposing a method of sharing which not only makes the Commission's sharing objective technically feasible, but which in itself evidences CELSAT's technical contribution to spectral efficiency in the RDSS band as well as potentially in others, and thereby supports CELSAT's request for a pioneer's preference. At the very least, it illustrates the strength of CELSAT's technical abilities in this field, and its ability to contribute as a potential member of the Commission's Advisory Committee.[5]

Accordingly, CELSAT hereby respectfully applies to the Commission to be included as an interested party on the Advisory

---

[5] CELSAT notes that the Commission has permitted LEOSAT to participate fully in the negotiated rulemaking sessions among the small LEO applicants even though LEOSAT is not itself an applicant.

Committee. As such, CELSAT's representative will represent both the interests of CELSAT and those of the other CDMA-based applicants who are willing to participate in MSS on a shared spectrum basis but which have not yet identified a technically sound or feasible method for accomplishing this. No other representative of a LEO applicant can be counted on to represent CELSAT's interest. While they might share CELSAT's willingness to share spectrum, their methods of doing so, to the extent that they have been disclosed to date, either are technically unworkable, not yet totally developed, or, worst of all, could by design unnecessarily preclude CELSAT and any other later applicant from participating in the RDSS band.

Finally, CELSAT commits that its representatives will participate fully and in good faith in the development of the rules under consideration. It will do so through one or other of its principals, David Otten, Dr. Jack Mallinckrodt, Victor Toth, Dr. Warren Morrison and Alan Frazier.

Respectfully submitted,
CELSAT, INC.

By: ______________________
Victor J. Toth

The Law Offices of Victor Toth, P.C.
2719 Soapstone Drive
Reston, Virginia 22091
(703) 476-5515

September 3, 1992

BAND-SHARING COORDINATION OF WIDE-BAND MOBILE SATELLITE SERVICES.

Jack Mallinckrodt
CELSAT
August 31, 1992

INTRODUCTION

The FCC has before it a number of applications envisioning band-sharing in the mobile satellite service. Some of these imply an unqualified ability and willingness to share the allocated band with other system proposers. Other applicants have put forth arguments that their system provides a more efficient means either alone, or band-sharing on an FDMA frequency basis. We argue that neither such extreme position is technically correct.

Even with the advantages of spread spectrum, the capacity that can be derived from a given band is a limited resource. As more sharing users are added to a given band, the general interfering background flux density increases proportionally and the circuit capacity of each other participant is diminished accordingly. Without appropriate flux density control This can result in a *significant reduction in total US capacity.*

We can best illustrate this with one of the results to be developed later in this paper. CELSAT proposes a system design which, on the basis of sole occupancy of a 16.5 MHz band at a flux density of 2.9 FDU[1] would provide approximately 60,000 US circuits capacity. Considering all the major CDMA proposers that are compatible in principle, (GLOBALSTAR B, ELLIPSO, ARIES, ODYSSY, and CELSTAR) their total proposed US capacity is 71,000 circuits in separate bands. *Sharing* a single band between these users, each at their requested flux density, would reduce their *total* US capacity from 71,000 to 33,000 circuits at a much greater flux density of 9.6 FDU. This is significantly worse than CELSTAR alone (60,000 circuits) at 2.4 FDU.

Cumulative flux density is the controlling factor in this issue. Thus in considering CDMA multiple band-sharing proposals, it may become incumbent upon FCC to devise means of *allocating flux density* as well as frequency bands, and to follow a sound mixed strategy of frequency division in multiple bands as well as CDMA band-sharing.

[1]. For convenience, the "FDU" is defined here as a unit of power flux density equal to -144 $dBW/m^2/4kHz$.

This paper develops the fundamental technical limitations on band-sharing. It develops simple bandwidth and flux density scaling algorithms so that diverse system proposals can be compared on a level field with respect to these limited, allocatable resources. It provides the means to estimate the effect of a given band-sharing/flux density allocation on individual system and overall US capacity. While directed to the MSS issue, it develops a methodology that may be of use to the FCC in deciding how best to allocate and manage such common function, multiple entry band-sharing allocations in other bands as well.

The reader not interested in the detailed developments to follow in the next few sections may skip from this point to the final "RESULTS" section on page 10 for a summary of findings including specific examples.

CODE CORRELATION

Band-sharing SSCDMA users potentially interfere with one another in two ways. The first and easier part of the coordination problem is Code Correlation. In order effectively to separate the various band-sharing signals, the spreading codes must be essentially "uncorrelated". If two users were to utilize identical band spreading pseudo-noise waveforms or codes, they could (when inadvertently synchronized) interfere with one another totally, as if they were FDMA users in the same frequency channel.

Ideally, all user codes would be *orthogonal*, that is, correlation would always be zero. But this is not generally possible, both because of the limited number of such orthogonal codes, and because orthogonal codes are only so at a particular relative phasing with respect to one another. In the MSAT service, the relative phases of signals from different sources are position dependent. So a set of codes that were orthogonal in one location would not generally be so in another except in the special case of multiple downlinks from a single satellite. Practically, to realize the full advantages of SSCDMA band-sharing, users must utilize codes that do not correlate more strongly than random noise of the same power and bandwidth. This decorrelation can be effected by the use of "sufficiently" (can be rigorously defined) different code generators, frequencies, or phases. Considering these dimensions, there are potentially far more than enough pseudo-random spreading waveforms to go around, given some minimal structured coordination. Rules for such coordination need to be developed, however.

RANDOM CODE INTERFERENCE

The second aspect is more difficult and relates to control of cumulative background interference level. To a particular CDMA user, the signals of each other band-sharing user, CDMA or otherwise, appear as additional random, Gaussian noise. When the cumulative spectral density of all such band-sharing users exceeds the natural thermal noise background by more than a few dB, then the band is effectively saturated; practically, no more band-sharing is possible. To introduce more band sharers, or for any one user to attempt to increase his capacity by amplifying his signal level above this general background in an unregulated manner can only lead to an ultimately non-productive, mutual escalation of transmitter power without any gain in signal/noise ratio for anyone.

We will develop the fundamental governing relations for this band-sharing limitation hierarchically,

- starting with a single CDMA circuit,
- then a single CDMA cell,
- then a single CDMA system of regional cells,
- then a summation of regional CDMA (or other) systems, all sharing a common spreading bandwidth, W.

In this paper we consider only the satellite to user downlink because this commonly plays the critical role in capacity determination.

SINGLE CIRCUIT

First consider a satellite-to-ground circuit, with no intra- or inter- system interference from other users. The transmitted signal is idealized as uniformly spread over a bandwidth **W** with areal power spectral density at the mobile unit, ρ_1 ($w/m^2/Hz$). Then the available[2] signal power S_1 at the user antenna terminals can be expressed as

$$S_1 \quad = \rho_1 \, A \; W \qquad \text{(Watts)}$$

where

$$A \quad = \text{user receive antenna capture, area}$$
$$\doteq G_r \lambda^2 / 4\pi \qquad (m^2)$$

In the present instance we are dealing with systems (almost) all of which are designed to serve mobile, handset users. Consequently it is not unreasonable to assume that all the competing systems have about the same antenna gain (about zero dB +/-) and, of course, all are operating at the same wavelength, λ. Subject to possible exceptions requiring special treatment, we thus take the capture area, **A**, as a system independent constant for most mobile satellite systems in given band (AMSC may be a mild exception).

The available[1] system noise power spectral density at the same terminals may be expressed

[2]. The term "available" here means the maximum power available from the antenna to a matched load.

$$N_o = k\,T_o\,NF$$

where

$k\,T_o$ = reference temperature thermal noise spectral density (W/Hz)

NF = Effective system noise figure including external noise (other than CDMA interference)

All of the systems of interest are assumed digital at the baseband, so the relevant SNR-like parameter is the dimensionless bit energy-to-noise-density ratio, $\Gamma \doteq E_b/N_o$ given by

$$\Gamma = S_1 / (N_o\,R) \qquad = \rho_1\,A\,W / (N_o\,R)$$

where **R** is the baseband digital rate.

To meet a suitable BER criterion, Γ is required to satisfy a certain minimum value, Γ_s, characteristic of the particular system (subscript **s**), typically 4 to 9 dB depending on details of modulation and coding. So we can solve for the required flux spectral density for a single circuit with no interference,

$$\rho_{1,s} = \Gamma_s\,N_o\,R / (A\,W).$$

Notation can be further simplified by defining an *effective thermal noise equivalent flux density,*

$$\rho_n = N_o / A$$

For a relevant example, consider N_o = **kTo** = -204.0 dBW/Hz, (i.e. thermal noise only), omnidirectional antenna at 2400 MHz. **A** = -29.0 dBm^{-2} and ρ_n = -138.9 dBW/m^2/4kHz. The high angle ITU flux limit, -144 dBW/m^2/4kHz, or 1 FDU, is thus 5 dB less than the thermal noise equivalent flux. Thus individual complying systems cause an interference level generally negligible as compared to thermal noise as clearly was the intention.

In these terms, the required flux density for a single signal (subscript 1) can be written:

$$\rho_{1,s} = \rho_n\,\Gamma_s\,\frac{R}{W} \tag{1}$$

In words, the minimum flux density for a single data channel is equal to the product of the equivalent noise flux density times the required **Eb/No** divided by the bandspread ratio, or processing gain, **W/R**.

SINGLE CDMA CELL

Now suppose that only one cell, that is one satellite beam, of one system is on the air. The system is subject to a flux density limit, ρ_s at the earth. How many circuits, M_s, can the system support in this one cell?

The thermal noise in this case is augmented by the CDMA noise from the other M_s - 1 circuits in system s. M_s is then given by the equivalent of Equation 1 above in which we substitute

ρ_s / M_s for $\rho_{1,s}$ (the single signal flux density)

and

$\rho_n + \rho_i$ for ρ_n

where

$$\rho_i = \text{Interference flux spectral density} \equiv (M_s - 1) / M_s \; \rho_s$$

Since M_s, the number of circuits for system s is generally much greater than 1 in the cases of interest, there is little error in assuming that the factor $(M_s - 1) / M_s$ is equal to 1. With these substitutions,

$$\Gamma_s = \frac{\rho_s \quad W}{(\rho_n + \rho_I)\; M_s\, R}$$

or

$$M_s = \frac{\rho_s \quad W}{(\rho_n + \rho_I)\; \Gamma_s\, R} \qquad (2)$$

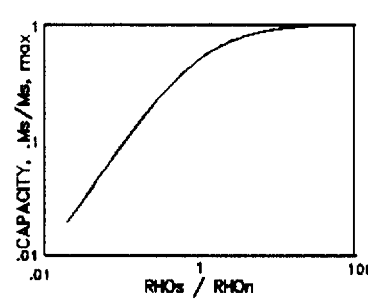
or

$$M_s = \frac{r}{1+r}\, M_{s_{max}}$$

where

$r \doteq \rho_s / \rho_n$ and $M_{s,max} \doteq W / (\Gamma_s R)$

This looks like this ---->>>>



For small ρ_s the capacity is proportional to ρ_s, that is, ultimately proportional to transmitter power. But as ρ_s becomes much larger than ρ_n, (the noise equivalent flux density) the maximum number of circuits supported by system s approaches the limiting constant,

$$M_s \rightarrow M_{max,s}$$

independent of ρ_s or transmitter power. Further increases in power, or flux density, ρ_s are unproductive in increasing system capacity since they raise the interference level as fast as the desired signal. Thus, $M_{max,s} = W / (\Gamma_s R)$, is the limiting CDMA circuit capacity of this simple, single cell example.

Some CDMA critics have noted that **W/R** is essentially the capacity of the same channel under Frequency Division Multiplex, and that therefore the limiting capacity of CDMA is smaller than FDMA by the factor $1 / \Gamma_s$. This would be true for a single cell system, but ignores the much larger gain in capacity due to frequency reuse factor that results from the unique CDMA ability to reuse the same spectrum in *each* cell of a multiple cell US coverage system.

SINGLE-SYSTEM, MULTIPLE-CELL REGIONAL COVERAGE

Generally, system regional capacity over an area such as the United States, can be increased by the use of small beams covering the region with a multiplicity of contiguous beams, that is, "cells". This provides a potential twofold advantage, 1) higher antenna gain, thus more total flux density for the same, limited transmitter power, (or lower power for the same flux density) and, 2) opportunity for reuse of the same spectrum in another part of the region. Both factors increase the total regional circuit capacity. Let NCR_s = Number of Cells per Region (e.g. United States) for system, s.

Frequency reuse among these cells, like co-channel reuse, comes at the cost of some additional co-channel interference. In general, and particularly in the case of FDMA where relatively little co-channel interference can be tolerated, it is necessary to put some distance, between co-channel users. The required distance separation in turn implies a "cluster size", NCC_s , (Number-of-Cells-per Cluster) which is defined as the minimum number of neighboring cells, each operating within a *different* subband, such that there be no co-channel interference between cluster members and that any cell outside the cluster is far enough away from a co-channel user within the cluster that his co-channel interference is tolerable. In the case of ground cellular users this cluster size is typically 7 or more. For FDMA satellite systems it may range from 3 to 7 while for CDMA systems it is generally but not always 1. We further define the Regional Frequency Reuse Factor, **RFRF** as

$$RFRF_s \triangleq NCR_s / NCC_s$$

A second important factor in consideration of regional coverage is "Cluster Overlap Factor", **COF**. It is possible in the case of CDMA to reuse the same frequency bands in every cell, that is, a cluster size of one. However, this is then at the price of possibly significant beam overlap or sideband spillover from one cell to the next. In the more general case of cluster sizes other than 1, the spillover from adjacent Clusters plays the same role. The effect of this spillover is a correspondingly increased background interference level and reduced circuit capacity. On the assumption of uniform loading of all cells, knowing the beam pattern, we can compute the amount of such spillover. We then define:

COF = **Cluster Overlap Factor**
$\triangleq$ (Total CDMA interference flux from all co-channel users in ***all*** clusters) / (CDMA interference flux from all co-channel users in ***own*** cluster)

In the common CDMA case where a cluster *is* a single cell,
the word "cell" can be substituted for "cluster" in the above definition.

To the extent that **COF** is a function of position within a cluster (or cell), the system **COF** is defined at the worst spot in the cell, i.e. that for which **COF** is maximum.

If the system is subject to a maximum, allocated flux density limit, $\boldsymbol{\rho}_{m_s}$, then the total interference flux is (at most) $\boldsymbol{\rho}_{m_s}$, while the intra-cluster (i.e. from within same cluster) interference flux is $\boldsymbol{\rho}_{m_s}$/**COF**. **COF** then is the amount by which the total flux per cluster (or cell) must be reduced due to finite beam spillover, in order to meet a prescribed maximum flux limit, $\boldsymbol{\rho}_{m_s}$.

With these definitions, the per cell capacity is given by (2) above with the substitutions:

W/NCC$_s$	for	**W**	(Since only 1/**NCC** of the total bandwidth can be used per cell) and
$\boldsymbol{\rho}_{m_s}$	for	$\boldsymbol{\rho}_i$	(total interference limit)
$\boldsymbol{\rho}_{m_s}$/**BOF$_s$**	for	$\boldsymbol{\rho}_s$	(only the own cell useful part of the total flux)

and the total regional capacity, $\mathbf{M}_{r_s}$ is thus from Equ. 2:

$$M_{r_s} = \frac{\rho_{m_s}}{\rho_n + \rho_{m_s}} \; Q_s \qquad (3)$$

where

$$Q_s \doteq \frac{NCR_s\, W}{\Gamma_s\, COF_s\, NCC_s\, R} \tag{4}$$

$\mathbf{Q_s}$ summarizes the intrinsic capacity determining elements of the system under the designers control, as opposed to the flux densities. It may be interpreted as the maximum possible regional system capacity if there were no flux density limits nor other band-sharing systems. Furthermore, within the above listed assumptions, it conveys all the necessary information about how effectively system s can share spectrum with other users. Notice that for the purpose of estimation, $\mathbf{Q_s}$ could be defined from equation 3 as the system capacity, normalized with respect to the system flux density as:

$$Q_s \doteq M_{r_s} \frac{\rho_{m_s}}{\rho_n + \rho_{m_s}} \tag{5}$$

This is used in the examples following.

For non-CDMA systems, essentially the same equation holds with the following understandings: 1) For FDMA and TDMA the overlap factor is essentially unity, because, in order to avoid unacceptable crosstalk, it is usually necessary that the co-channel interference be much smaller than random noise, 2) this is achieved by having a larger cluster size, **NCC**. In effect, overlap factor, **COF**, is traded for cluster size, **NCC**, and 3) system flux density, refers to the band average flux density, over the band, **W**. Thus the power areal density (integrating over the entire band, **W**) is , by definition, $\boldsymbol{\rho}$ **W**.

MULTIPLE SYSTEM, REGIONAL COVERAGE, FLUX ASSIGNMENT

Finally, we consider the case where multiple systems are assigned to the common band, **W**.

Inevitably, the flux density used by other users will reduce the capacity of each such band sharer system relative to what would be that case if that system had the band to itself. In the sharing mode, if there were no flux density allocations, or agreements, then, in principle it would be possible for one user to (temporarily) "steal" most of the inherent capacity of the band by increasing his transmitted power and flux density to well above that of the others. Ultimately, however, this could only result in a mutually fruitless escalation of power and flux density. No one would gain and all would lose power efficiency. Of course this would be to the detriment not only of the band sharers but of all other incidental interference victims, such as radio astronomy services etc.

This potential must be recognized and provided for by firm agreements or flux density allocations administered by the FCC. For the moment we assume that such individual system flux density limits are in place by one mechanism or another, each sharer system, s, being assigned and using a maximum flux density ρ_s. What is the resulting individual system and overall band capacity?

The total interfering flux density is given by the summation over all sharing systems of the individual system maximum flux density allocations

$$\rho_I = \sum_s \rho_{m_s}$$

Each system then must satisfy its own SNR requirements by restricting its capacity or number of circuits to that given by equation 2 above, except that now ρ_i and $\rho_s = \rho_{m_s} / COF_s$ are set by allocation rather than necessarily the power limits of his own system or overall flux density limits such as the ITU limits.

That is, the regional capacity of the s[th] system is given by:

$$M_{r_s} = \frac{\rho_{m_s}}{\rho_n + \sum_s^{NS} \rho_{m_s}} Q_s \qquad (6)$$

For FCC purposes, the result of this sharing is best expressed in its effect on overall combined regional circuit capacity over a service region of interest such as the United States. The total regional capacity, summing over all systems is:

$$M_r = \sum_{s=1}^{NS} M_{r_s} \qquad (7)$$

If all sharing systems are allocated *equal* flux density, ρ_m so that

$$\rho_i = \sum \rho_{m_s} = NS\, \rho_{m_s}.$$

Then from 6) , the individual system capacity reduction due to sharing would be in the ratio,

$$\frac{M_{r_{s_{shared}}}}{M_{r_{s_{alone}}}} = \frac{\rho_n + \rho_m}{\rho_n + NS\, \rho_m} \geq \frac{1}{NS} \qquad (8)$$

Thus the individual capacity of system s with sharing lies somewhere between that of system s alone and 1/NS of that alone. ***If all systems were equal** in terms of their individual regional capacities at the same flux limit, non-shared, then the total capacity with sharing would exceed the sum of the individual unshared capacities.* This unstated qualification is implicit in the abbreviated Loral-Qualcomm claim to this effect (Loral-Qualcomm consolidated reply, March 27, 1992, Technical Appendix, p.8). However, more generally, if all systems are *not* equal in terms of regional capacity, (or $\mathbf{Q_s}$), then, allocating the same flux density to each, thus reducing each system capacity by the roughly the same ratio, even though that ratio is greater than 1/NS, *may result in a significant net loss of overall regional, i.e., US capacity* as compared to allocating strategies designed to encourage the development of higher capacity systems.

RESULTS

1.SYSTEM NORMALIZATION

With a few commonly applicable assumptions, equations 4 or 5, 6 and 7 provide the basis for comparing diverse systems on a level playing field with respect to their utilization of the allocatable resources, flux density and frequency bandwidth. Additionally they allow the comparison in terms of overall US benefit of various alternative allocation strategies.

The required assumptions for mobile satellite systems are that:

1. The system capacity is essentially determined by the limitations of the satellite-to-mobile down-link.
2. The system capacity is determined by flux density limits and not by available satellite power.

Both points are implicitly recognized by a majority of the current mobile satellite applicants, in that they and CELSTAR have proposed and requested variance above the one FDU or -144 dBW/m^2/4kHz ITU flux density limit. Even when the above two assumptions are not perfect it appears that they are a reasonable first assumption leading to a useful first approximation for the effects of system flux density and bandwidth normalization and-sharing.

Table 1 shows the results of the capacity normalizing algorithms given in the preceding sections. To make the normalization examples as relevant as possible, the comparison is put in terms of the actual design parameters of the major Mobile Satellite proposers. This requires abstracting from the documentation, three parameters:

- Total satellite-to-mobile Bandwidth, MHz
- Flux Density, dBW/m^2/4kHz at the ground
- US circuit capacity

for the Satellite-to-Mobile downlink, in order to evaluate the fundamental system capacity parameter, **Qs**, by equation 5.

It is not easy, and it may be impossible in some cases to extract these parameters unambiguously from the applications. In some cases there are partially alternative systems, or parameter update inconsistencies in various parts of the documentation. The data in columns B, C, and E of Table 1 are our best effort at extracting the correct and relevant parameters. Since inevitably there will be errors in this process we apologize in advance, will gladly correct them as informed, and ask the reader to regard the results as examples of a methodology based upon hypothetical systems which are generally like the actual proposed systems.

Under the above assumptions, for a given flux density, circuit capacity is directly proportional to bandwidth. So column F of table 1 represents the first step in normalizing the stated US circuit capacity, by linear proportion, to a common bandwidth, here taken as 16.5 MHz.

Column G is the system characteristic capacity, normalized to a common (infinite) flux density, i.e., Q_∞, as given by equation 5, and common bandwidth, 16.5 MHz. This is the *limiting* capacity for very large flux density, (and satellite transmitter power) so may be well over the nominal capacity, particularly for systems such as ARIES, designed for significantly less than 1 FDU flux density. As a result of this normalization systems such as IRRIDIUM, ODYSSY, AMSC and CELSTAR suffer the greatest reduction of flux density from their original requests, and correspondingly greatest reduction of their nominal capacity. The flux density normalization implicitly assumes the feasibility of trading circuit capacity for flux density, which may not be the case for non-CDMA systems such as AMSC.

Column H of Table 1 is then the normalized real capacity of the system, reduced to common bandwidth, and a common nominal flux density of one FDU[1]. In all cases this nominal capacity is just 24% of the reference capacity, Q_∞. It is suggested that comparison in this normalized form provides a fairer picture of the relative spectral utilization efficiency of the various systems. For example, it is seen that much of IRRIDIUM's high circuit capacity is related to its relatively large assumed flux density, about 13 FDUs. Accordingly, its 1 FDU normalized capacity suffers significantly. The bottom row (row 15) of column H is the summed capacity of all the proposed systems, each allocated 16.5 MHz and 1 FDU separately, US circuits.

2. Band-sharing EXAMPLES

Table 2 carries out several example joint allocations using this capacity renormalization methodology to illustrate the results of various flux density allocation strategies. For these hypothetical comparisons, we include only the clearly compatible, frequency duplexed, CDMA systems of Table 1, that is, GLOBALSTAR B, ELLIPSO, ARIES, ODYSSY, and CELSTAR.

In scaling the system capacities to various allocated flux densities according to equation 3, it must be borne in mind that flux densities *greater* than the design values would call for increased power and concomitant system redesign which might or might not be feasible, a separate question that would have to be investigated for each proposed allocation. Again, in this respect, the results are hypothetical, a first estimate, to be carefully reviewed for the applicability of other constraints in each case.

The first two columns (B and C) in Table 2 are the reference capacity, Q_*, and the capacity at nominal flux density of 1 FDU (the ITU high angle limit) for each system as derived in Table 1. Notice that the total normalized capacity of the systems separately at 1 FDU each is 40,298 circuits, given on the bottom line of column C.

Thereafter in Table 2, columns occur in pairs, representing respectively the assumed joint flux density allocation (measured in FDUs), and the resulting individual system capacity by equation 6. Total flux density and capacity over all systems are given in the bottom row.

CASE 1 is the nominal example of each system allocated and using 1 FDU shared over a common 16.5 MHz bandwidth. Total US capacity has decreased from 40,300 separately to 20,700 jointly, a 50% loss which also applies to each system individually due to the increase of total interference background from 1 to 5 FDU. The individual reduction factor may in fact be greater than this for GLOBALSTAR B since, by the use of orthogonal spreading codes on her down link, her self interference is much reduced and she suffers proportionately more in a sharing environment.

CASE 2 illustrates each sharer using two (as compared to one in CASE 1) FDU. This shows the saturation effect as doubling the flux density affords only a 25% increase in US circuit capacity. The point of significantly diminishing returns is somewhere around 5 FDU which is about equal to the thermal noise background flux equivalent, 138.9 dBW/m^2/4kHz.

CASE 3 illustrates the results of giving each system what they have asked for in terms of flux density. This is a total of 9.6 FDU and yields a total capacity of 34,000 US circuits. Note that this is about half that of CELSTAR alone, but at 4 times CELSTAR's proposed flux density.

CASE 4 illustrates an initial attempt at optimizing the allotted flux density shares, with an eye to maximizing overall capacity and affording a stronger incentive toward more spectrally efficient designs. In this case, the total flux density of 10 FDU is allotted in proportion to the normalized, reference capacity of the system, Q_*. Two things are obviously wrong with this: 1) It is much too strong an incentive, CELSTAR gets the lion's share of the flux, much more in fact than could be utilized within the overall prime power constraint of the CELSTAR design, and 2) the penalty on the less efficient system is so strong as to reduce ARIES, for example, to a single circuit; obviously non-viable.

CASE 5 is an attempt to do just a little bit of what CASE 4 was trying to do. In this case, the total flux of 10 FDU is allocated in proportion to the 0.15 power of the individual Q_s. In this case several of the systems come out reasonably close to what they have originally proposed.

Within the limited range of possibilities explored here, CASE 3, giving each applicant what they ask for in terms of flux density, within the general constraints of band-sharing compatibility seem to afford a reasonable solution. However this is at a sacrifice of almost half the potential capacity if it were possible to grant each system exclusive frequency bands. Clearly an optimum solution calls for some joint use of frequency division in addition to band-sharing.

IN SUMMARY

The era of band-sharing is here. New regulations and approaches to allocation are called for to make this work. The spectrum allocation problem must be seen to have acquired a new dimension, flux density, in which allocation is as important as the allocation of frequency band if the full potential benefits of band-sharing are to be realized.

In some cases band-sharing may result in overall gain in US capacity. In other cases it may have the opposite effect, loss of overall US capacity as well as individual system capacity and economic viability.

This paper does not develop or advocate any particular flux density sharing allocation policy. It does, however, provide the essential means to study the effect of different individual and total flux density allocations on individual and total US capacity.

Some such methodology is seen as an essential element in realizing the FCC objective of managing the RF spectrum to the maximum overall national benefit.

TABLE 1

	A	B	C	D	E	F	G	H
1		INDIVIDUAL SYSTEMS NORMALIZED						
2							Qs	Ms
3		DESIGN PARAMETERS				BW	BW & FD	@ FD =
4						NORMALI	NORMALI	1 FDU =
5						Bo=	FDnoise=	-144
6		BW	FLUX DEN	FLUX DENS		16.5	-138.9	
7		MHz	dBW/m2/4	FDUs (1)	US CKTS	US CKTS	US CKTS	US CKTS
8	IRRIDIUM	10.5	-132.8	13.18	3835	6026	7506	1772
9	GLOBALSTAR	16.5	-145.0	0.79	5000	5000	25369	5989
10	ELLIPSO	16.5	-144.0	1.00	864	864	3660	864
11	ARIES	16.0	-148.6	0.35	50	52	533	126
12	ODYSSY	16.5	-137.4	4.57	4600	4600	7857	1855
13	CELSTAR	16.0	-139.4	2.88	60905	62808	133280	31464
14	AMSC	14.0	-139.0	3.16	3000	3536	7154	1689
15	TOTALS				71419		170699	40298
16	1. FDU: Flux Density Unit equal to -144 dBW/m^2/4kHz							

TABLE 2

EXAMPLES OF JOINT ALLOCATION

	A	B	C	D	E	F	G	H	I	J	K
1				CASE 1		CASE 2		CASE 3		CASE 4	
2		Qs	Ms,144	FDalloc	Ms, shrd	FDalloc	Ms, shrd	FDalloc	Ms, shrd	FDalloc	Ms, shrd
3	SYSTEM	US Ckts	US Ckts	FDUs	US Ckts	FDUs	US Ckts	FDUs	US Ckts	FDUs	US Ckts
4	GLOBALSTAR	25369	5989	1	3080	2	3833	0.8	1522	0.74	1469
5	ELLIPSO	3660	864	1	444	2	553	1.0	277	0.11	31
6	ARIES	533	126	1	65	2	81	0.3	14	0.02	1
7	ODYSSY	7857	1855	1	954	2	1187	4.6	2713	0.23	141
8	CELSTAR	133280	31464	1	16183	2	20139	2.9	29041	3.90	40549
9	TOTAL	170699	40298	5	20726	10.0	25793	9.6	33567	5	42190
10											
11		CASE 5		CASE 6		CASE 7		CASE 8		CASE 9	
12		FDalloc	Ms, shrd	FDalloc	Ms, shrd	FDalloc	Ms, shrd	FDalloc	Ms, shrd	FDalloc	Ms, shrd
13	SYSTEM	FDUs	US Ckts	FDUs	US Ckts	FDUs	US Ckts	FDUs	US Ckts	FDUs	US Ckts
14	GLOBALSTAR	1.2	3561		0		0		0		0
15	ELLIPSO	0.8	349		0		0		0		0
16	ARIES	0.5	35		0		0		0		0
17	ODYSSY	0.9	872		0		0		0		0
18	CELSTAR	1.6	26068		0		0		0		0
19	TOTAL	5	30885	0	0	0	0	0	0	0	0

20 * 1 FDU := -144 dBW/m^2/4kHz